Backward production on nuclei and the tube model

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It is shown that the recent data from Burke *et al.* on backward production in 200-GeV/c nA collisions are in good agreement with expectations from the collective tube model with tube fragmentation taken into account.

The inclusive spectrum of $nA \rightarrow$ all charged + X with neutron momenta of around 200 GeV/c has recently been measured at extreme backward angles, $\eta \equiv -\ln \tan(\theta_{\text{lab}}/2) = -2.8$ to -1.6 , and with Be, Cu, and Pb targets.¹ The size of the target nucleus (mass numbers $A = 9, 64$, and 208 , respectively) seems to influence the cross section $\sigma_{\text{inel}}^{-1} d\sigma/d\eta$ only through a factor $A^{1/3}$ relative the corresponding yield in pp collisions. This is no surprise, because similar factors appear also in data from other experiments.^{2,3} In addition, the factor $A^{1/3}$ represents also the growth of the nuclear radius with growing A , which hints at some simple explanation of its presence in backward spectra.

A controversial conclusion in the paper by Burke *et al.*¹ is, however, the statement that backward yields are in "disagreement with naive coherent tube models." The aim of this Comment is to show that such a conclusion is questionable and that the coherent (collective) tube model (CTM) in our interpretation is in an almost trivial agreement with data (for reviews of the CTM see Refs. 4–6).

When analyzing data on backward yields, in any kind of collision and within any model, one has to take into account that the backward part of rapidity spectra is *dominated by target fragments*. This fact was not considered in a quantitative way by the authors of Ref. 1. In their analysis of the CTM they confronted data in the target fragmentation region with "predictions" from an equation derived and valid only for *target-independent* quantities. Nothing could in fact depend more on the detailed quantum properties of the target than its own fragmentation. This restriction of the so-called universality equation is quite clear from its structure and derivation, and also stated in the original literature (see Refs. 4–6 for references) and in particular in the CTM papers by Afek *et al.* and by us quoted in Ref. 1.

The crucial statement in Ref. 1 that "except for

its mass the tube behaves like a nucleon," sometimes mistakenly believed to be the *definition* of the CTM, is just a simplification for production mechanisms that are known to depend only on the collision energy, and is hence not applicable to the backward data of Burke *et al.* The true definition of the CTM is that the tube behaves like one single *particle*^{4–6} with the full mass, quantum number, and quark content of the tube. A tube-"particle" can for instance not decay or fragment like one single nucleon.

A CTM treatment of backward production of tube fragments turns out to be simple, because a tube with i nucleons naturally decays (fragments) to around i times the number of particles one gets from the fragmentation of one single nucleon. Since $\langle i \rangle \approx A^{1/3}$, the measured A dependence is easily understood qualitatively.

To get also the quantitative expectations from the tube model, one has to take into account that tube fragmentation is a two-step process; the tube *recoils* in a collective manner and then *decays* to nucleons and pions (decay products such as heavy fragments, kaons, etc., are neglected). A detailed scheme for treating these processes was presented in Refs. 7 and 8. There we assumed that the tube recoils collectively like a single nucleon in a projectile-nucleon collision, i.e., that the (Feynman-scaled) x spectra of $h + \text{tube} \rightarrow \text{tube} + X$ and $h + N \rightarrow N + X$ are equal in the respective c.m. systems. This simple assumption has been shown⁸ to be supported by the existing data on recoil-nucleon spectra. After the collective recoil, the individual nucleons in the tube are assumed⁷ to spread out and fragment independently. This gives the inclusive cross section $f^{hA \rightarrow tX} = \sigma_{\text{inel}}^{-1} \times d\sigma/d\eta$ of any kind of target fragment t :

$$f^{hA \rightarrow tX}(p_{\text{beam}}, \eta) = \sum_{i=1}^A i P(i, A) f^{hN \rightarrow tX}(p_{\text{beam}}/i, \eta), \quad (1)$$

where $P(i, A)$ is the probability to hit a tube with i nucleons in a nucleus with A nucleons, and where

$f^{hN \rightarrow iX}$ is the cross section with a nucleon target.

Backward yields are dominated by target fragments in both hA and hN collisions, so we can use data from, for instance, pp collisions as direct input in Eq. (1). The velocity cuts, $p > 0.1$ GeV/c for pions, 0.35 GeV/c for protons, in the data of Ref. 1 have small effects on tube fragments at $\eta \approx -2$, although slow protons from the decay of the remnants of the nucleus are effectively eliminated. In addition, protons from the tube have kinematic difficulties to get to large backward angles, and can be neglected compared to the yield of tube pions in this analysis.

As a practical input for Eq. (1) we use the radii-scaling parametrization⁹ for $pp \rightarrow \pi X$:

$$Ed\sigma/d^3p = B(1 - x_R)^N g(p_T), \quad (2)$$

which is known to reproduce data accurately in the target-fragmentation region. Here $x_R = 2p/\sqrt{s}$, $B = 230$ (GeV/c)⁻², $N = 3$, and $g(p_T) = \exp[-6(p_T^2 + m^2)^{1/2}]$. Although the authors of Ref. 1 do not reveal the details of their analysis, this should essentially be the same input they used for pp data in the "universality" equation.

After transforming to fixed η and integrating over p_T , we get the results shown in Fig. 1, together with data from Ref. 1. It can be seen that backward spectra are practically proportional to $A^{1/3}$ for all $\eta \lesssim -1$ and for all target nuclei, which

FIG. 1. The backward η spectra of Burke *et al.* (Ref. 1) compared with tube-model estimates ($\sim A^{1/3}$ times pp data) as well as with the conjecture that target fragments are $\langle v \rangle$ times as numerous as in pp . For $n\text{Pb}$ collisions $\langle v \rangle \approx 0.7 A^{1/3} \approx 4.3$ has been used.

is in good agreement with data. This naturally reflects, via Eq. (1), the fact that the dependence on p_{beam} is very weak (limiting fragmentation). The conclusion is therefore that the *detailed* mechanism for tube decay is not essential for understanding the observed A dependence, as long as the tube fragments roughly like a bunch of i single nucleons.

Models with several independent projectile-nucleon collisions are in most respects orthogonal to the CTM. In the backward region, however, some of these models seem to expect spectra to grow in direct proportion to the number ν of nucleons that interact inelastically with the projectile. This is, for instance, the case in models where one postulates that intranuclear cascades do not occur. It must be remembered, however, that such models have $\langle \nu \rangle \approx 0.7 A^{1/3}$ (for $A \geq 10$) in pA and nA collisions. Hence $\langle \nu \rangle$ in conventional models is smaller than our $\langle i \rangle$ in the CTM. This comes about because i means the total number of nucleons in the tube, while ν includes only those nucleons that, according to a Glauber calculation, collide inelastically with the projectile. For comparison, we have plotted $\langle \nu \rangle$ times pp data for a Pb target in Fig. 1.

In conclusion, we have shown that the tube model, with our scheme for tube fragmentation, is in good agreement with backward η spectra from nA collisions at 200 GeV/c. The opposite conclusion in a paper by Burke *et al.*¹ is correct only if target fragments can be neglected in the target fragmentation region or if such fragments are produced by a mechanism which is sensitive to the collision energy only and not to the detailed quark structure of the target. We believe one has to take into account, in all models, that such hadrons on the contrary *dominate* at backward angles and that they are produced in proportion to the number of quarks in the target.

Note added in proof. In the following paper¹⁰ Burke and Longo criticize our CTM scheme by calling it "a more complex model" and by claiming that it violates energy conservation. We agree on both points. Our CTM scheme for backward production is more complex than that of Burke *et al.*,¹ but still is the simplest credible picture we can think of for collective tube fragmentation. As for our ability to "deal properly with kinematics," we have made one approximation, namely when defining the variable x in our Feynman-scaled recoil spectrum, whereby we assume that $\sqrt{s} \gg m_{\text{target}}$. This approximation is standard, and can be found implicit for instance in Ref. 1 by Burke *et al.* as well as in Feynman's original paper.¹¹ Taking the unphysical limit $m_{\text{tube}} \rightarrow \infty$ in our Eq. (1) therefore leads to the paradox pointed

out by Burke and Longo.¹⁰ The same paradox appears in the "universality" relation used by Burke *et al.* in Ref. 1, where the consequence is that the bulk of pions will be produced at $y_{\text{lab}} = -\infty$ as $m_{\text{tube}} \rightarrow \infty$. Using the exact definition of x , one naturally recovers, in both schemes, a symmetric spectrum in the laboratory as $m_{\text{tube}} \rightarrow \infty$, while the correction to our Eq. (1) is negligible for the $\sqrt{s}$ and A values

of Ref. 1. The concept of Feynman scaling can certainly not by itself violate energy conservation.

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